

BELLCOMM, INC.

1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Correlation of Predicted, Ground
Test, and Flight Thermal Behavior
in Apollo - Case 620

DATE: September 5, 1968

FROM: D. P. Woodard

ABSTRACT


Predicted temperatures are compared with temperatures measured during ground tests and several Saturn/Apollo flights. Approximately 70% of the flight measurements agree with predicted temperatures within $\pm 18^{\circ}\text{F}$ and 86% are within $\pm 36^{\circ}\text{F}$. During orbit, 71% of the measured temperatures are within $\pm 18^{\circ}\text{F}$ and 84% are within $\pm 36^{\circ}\text{F}$. Steady-state thermal SM simulations conducted by Lockheed indicate 85% of their measurements agree with predicted values within $\pm 20^{\circ}\text{F}$; 85% of their transient measurements were within $\pm 30^{\circ}\text{F}$ of their predicted values.

(NASA-CR-97634) CORRELATION OF PREDICTED,
GROUND TEST, AND FLIGHT THERMAL BEHAVIOR IN
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MEMORANDUM FOR FILE

In an effort to explore the current art of predicting spacecraft temperatures and flight thermal behavior in the Apollo Program, post-launch mission reports originating both at MSC and MSFC have been reviewed, together with the results of a series of experimental tests on Service Module thermal models performed by Lockheed.¹ The type and extent of data currently available for determining prediction capability is summarized in Table I.

As indicated, the bulk of available predicted-measured temperature comparisons has been gathered during ascent for selected portions of the S-I and S-IV stages. Flight temperature measurements on the SM and SLA are meager, reported only on flights AS-202 and AS-501. Only AS-501 and SA-7 contain orbital data. The Lockheed reports contain comprehensive and exhaustive predicted vs. measured temperature comparisons for the SM.

Aerodynamic Heating

In general the MSFC post-launch mission reports contain time-history comparisons of computed predictions and thermocouple measurements during the first 140-180 seconds of flight. To avoid excessive curve duplication and discussion, the data are assembled in Table 2 in terms of the approximate number of measurements and the corresponding number falling within $\pm 18^{\circ}\text{F}$ and $\pm 36^{\circ}\text{F}$ of the predicted temperatures. Where the measured temperatures have not been given as discrete points but as continuous, unmarked curves, equivalent points have been chosen at 10 second time intervals.

¹ See attached list of documents.

In some instances both pre-flight prediction and post-flight simulations have been compared to measurements. In these cases, measurements have been compared to the post-flight simulations in an effort to reduce the effect of known causes on the differences. The blanks in Table 2 indicate a general lack of standardization of data from flight to flight and the inadequacy of the seven categories chosen here to include the complete range of reported data.

The tabulated percentages indicate that from 59% to 79% of the aerodynamic temperature measurements are within $\pm 18^\circ\text{F}$ of the predicted values, whereas about 80% to 97% of the comparisons agree within $\pm 36^\circ\text{F}$. On a gross total basis, of the total 1206 data points, 71% and 86% are within $\pm 18^\circ\text{F}$ and $\pm 36^\circ\text{F}$ respectively.

Orbital Temperatures

S-IV Stage

Predicted and measured orbital temperature histories of the SA-7 S-IVB stage show good correlation. Of the approximately 84 measurements made on the S-IVB forward interstage, LH_2 tank, and aft skirt by some 9 thermocouples, 76% fall within $\pm 18^\circ\text{F}$ of prediction and 88% are within $\pm 36^\circ\text{F}$. Seven of the 84 measurements are outside the $\pm 36^\circ\text{F}$ limit because of partial debonding of the sensor. These measurements were recorded for the first 1.5 hours after insertion of the S-IVB into orbit. Similar measurements made on AS-501 for 3 thermocouples located on the S-IVB APS fairing are well within the maximum and minimum temperatures predicted. Of 43 LH_2 tank skin temperatures reported on AS-501, 63% are within $\pm 18^\circ\text{F}$ and 77% are within $\pm 36^\circ\text{F}$.

Command Module

The CM heat shield thermal response was measured during the coast ellipse phase of the AS-501 flight. Recorded temperature-time histories show cold-soak ablator temperatures 5 to 20°F greater than predicted values. This consistent discrepancy is believed due to uncertainties in insulation conductivity and to sensor area coupling to the CM substructure resulting in a slower than expected thermal response. Hot-soak ablator temperature measurements agree with predictions within $\pm 10^\circ\text{F}$ using an α/ϵ of .54.

Service Module Simulations Tests

Lockheed - California has conducted an extensive series of thermal simulations on a number of test models leading ultimately to a 1/3 - scale representation of the Apollo Service Module². Their experiment was designed to verify analytical prediction techniques beginning with a simplified SM model to study internal heat transfer and progressing to a model showing successful integration of internal and external heat transfer effects. The tests were made under laboratory type conditions, such that both experimental and predicted errors should be minimal. For all models tested during steady-state simulations, 85% of their predicted temperatures were within $\pm 20^{\circ}\text{F}$ of the measured values. Correlation during simulated engine firings show 60% of their predicted temperatures are within $\pm 15^{\circ}\text{F}$ of experimental measurements and 85% fall within $\pm 30^{\circ}\text{F}$. Their final analytical thermal model of the SM contained 260 nodes and 785 conduction and radiation resistors.

Lockheed considers the correlation of predicted and experimental temperatures obtained during these tests to have verified their analytical techniques and assumptions. Additional efforts are recommended by Lockheed, however, that would lead toward more accurate, but simplified, techniques for analyzing radiation heat transfer for complex models, better techniques for analyzing fluid storage and pressurization simulations, and improved techniques for relating thermal network complexity to analysis accuracy.

Conclusions

For the several Saturn Apollo flights considered, approximately 70% of the temperature measurements made during ascent are within $\pm 18^{\circ}\text{F}$ of their predicted values; 86% agree within $\pm 36^{\circ}\text{F}$. During orbit, 71% of the reported measured temperatures agree with predictions within $\pm 18^{\circ}\text{F}$ and 84% are within $\pm 36^{\circ}\text{F}$. Static thermal simulations on SM models made by Lockheed indicate that 85% of their measurements agree with prediction to within $\pm 20^{\circ}\text{F}$. The close correlation of these results is surprising in view of the diverse origins and conditions of these data.

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Attachments
Tables I-II
References

²

Their tests total 110 hours of space simulation and required over 50 hours of IBM-7094 time for analytical prediction and data reduction.

TABLE I

AVAILABLE DATA

CORRELATION OF PREDICTED AND MEASURED TEMPERATURES

FLIGHT	AERODYNAMIC HEATING				ORBITAL HEATING			TEST CHAMBER
	S-I	S-II	Location S-IV	SM	SLA	S-IV	Location CM	
SA-3	✓		✓					Simulation SM
SA-5	✓		✓					
SA-6	✓		✓					
SA-7	✓		✓					
AS-202	✓		✓	✓	✓	✓		
AS-203	✓		✓					
AS-204	✓		✓					
AS-501	✓	✓	✓	✓	✓		✓	
LOCKHEED								✓

TABLE II

S-I AERODYNAMIC HEATING

S-I UPPER TAIL SHROUD

FLIGHT	S-I UPPER TAIL SHROUD	
	Data Points	N +36°F
SA-3	-	-
SA-5	-	-
SA-6	-	-
SA-7	-	-
AS-202	17	14
AS-203	17	15
AS-204	15	4
AS-501	-	-
TOTALS	49	36
PERCENTAGES		67 90

S-I LOWER TAIL SHROUD

FLIGHT	S-I LOWER TAIL SHROUD	
	Data Points	N +18°F +36°F
SA-3	-	-
SA-5	-	-
SA-6	-	-
SA-7	-	-
AS-202	13	8
AS-203	23	18
AS-204	15	14
AS-501	-	-
TOTALS	51	40
PERCENTAGES		78 92

S-I FIN SIDE PANEL

FLIGHT	S-I FIN SIDE PANEL	
	Data Points	N +18°F +36°F
SA-3	-	-
SA-5	256	230
SA-6	32	24
SA-7	-	-
AS-202	120	61
AS-203	-	-
AS-204	-	-
AS-501	39	15
TOTALS	447	315
PERCENTAGES		70 82

SA-3
SA-5
SA-6
SA-7
AS-202
AS-203
AS-204
AS-501

TOTALS

PERCENTAGES

S-IV AERODYNAMIC HEATING

FWD SKIRT SKIN

FLIGHT	FWD SKIRT SKIN	
	Data Points	N +18°F +36°F
SA-3	-	-
SA-5	-	-
SA-6	-	-
SA-7	-	-
AS-202	17	17
AS-203	17	17
AS-204	19	9
AS-501	39	23
TOTALS	92	66
PERCENTAGES		72 80

LH₂ TANK

FLIGHT	LH ₂ TANK	
	Data Points	N +18°F +36°F
SA-3	-	-
SA-5	21	8
SA-6	32	18
SA-7	30	17
AS-202	17	17
AS-203	17	17
AS-204	42	25
AS-501	32	20
TOTALS	191	112
PERCENTAGES		59 85

AFT SKIRT SKIN

FLIGHT	AFT SKIRT SKIN	
	Data Points	N +18°F +36°F
SA-3	-	-
SA-5	-	-
SA-6	-	-
SA-7	-	-
AS-202	37	29
AS-203	51	43
AS-204	34	23
AS-501	60	56
TOTALS	134	91
PERCENTAGES		79 97

APS FAIRING FOREBODY

FLIGHT	APS FAIRING FOREBODY	
	Data Points	N +18°F +36°F
SA-3	-	-
SA-5	-	-
SA-6	-	-
SA-7	-	-
AS-202	16	16
AS-203	25	24
AS-204	-	-
AS-501	-	-
TOTALS	19	9
PERCENTAGES		10 51

SA-3
SA-5
SA-6
SA-7
AS-202
AS-203
AS-204
AS-501

TOTALS

PERCENTAGES

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